A GENERAL PURPOSE VEHICLE POWERTRAIN MODELING AND SIMULATION SOFTWARE - VPSET

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ABSTRACT

VPSET (Vehicle Powertrain Systems Evaluation Tool) is vehicle modeling and simulation software to analyze performance and fuel economy of conventional and hybrid powertrains. VPSET has a Graphical User Interface (GUI) to guide the user during building a vehicle model. This paper discusses VPSET, its organization, structure, vehicle templates and presents validation results for select vehicles.

KEYWORDS Vehicle powertrain, modeling and simulation, hybrid vehicles, hybrid powertrains

1. INTRODUCTION

Fuel economy is a growing concern in the transportation sector. Another key concern for the transportation industry is the reduction of engine emissions (CO_2 and PM) which contribute in a significant way to the greenhouse effect and ultimately global warming.   These have been the driving impetus for incremental improvements in efficiency of new engine designs and radical changes in powertrain designs, such as electric, hybrid electric and plug-in-hybrids.   It is absolutely critical that before any new powertrain designs are built, they should first be analyzed and optimized using state of the art modeling and simulation tools.

This paper presents a general purpose vehicle Modeling and Simulation (M&S) tool that designers can use to analyze their designs before purchasing any hardware or bending any metal. VPSET is a forward looking tool, with the ability to perform vehicle fuel economy and performance predictions of a conventional or a hybrid powertrain. In the forward looking VPSET, a driver sends the power controller a torque demand, which is then met by the power sources taking into consideration the limitations of each power source. Numerical integration techniques are used to compute system states based on system inputs (driver accelerator/brake command). In a backward tool, such as DOE's Advisor® [1], the speed and position of the vehicle is assumed to be known and the required forces and power are computed algebraically. While backward looking M&S tools are faster than forward looking tools in execution time by at least two orders of magnitude, forward tools better mimic "real world" behavior and are therefore better suited for power controller algorithm design and Hardware in the Loop (HIL) applications.

The following sections describe VPSET in more detail with validation examples using field obtained vehicle data. The structure of the tool, its organization, libraries and components are discussed in more detail.

2. STRUCTURE

VPSET has a modular structure of super libraries, sub libraries, and component models. The main libraries of VPSET include: (i) Powertrain components; (ii) utilities; (iii) vehicle templates; (iv) scaling; and (v) C functions. The Powertrain super library is the largest of all libraries with sub-libraries of mechanical and electrical accessories, driver, energy storage, fuel storage, electric machines, drive cycles, vehicle, aftertreatment, transmission, engines, and power controller. The

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utility library contains modules that perform vehicle energy analysis, performance analysis, fuel economy predictions, pre-check and post-check analysis and driving cycle analysis. The vehicle template library contains pre-defined vehicle templates for conventional, typical series and parallel hybrid powertrains. These templates are generic enough to model most vehicular powertrains. The scaling library includes scaling routines for all VPSET supported components that automatically scale up or scale down the user provided data to meet user defined powertrain requirements. The C function library contains specialized functions that were developed in C and integrated into VPSET to enhance the present functionalities of the underlying software.

Table 1 summarizes the main sub-libraries of the largest super library, "Powertrain Components". All the components within a sub library are interchangeable since they share the same input-output structure. Therefore, an automatic transmission can be switched with a manual transmission without any modifications to the overall vehicle model. The components of Table 1 are table look up based and do not contain high fidelity physics based models. It is entirely possible to use user-provided high fidelity component models as long as the input-output structure of the new model complies with the original component model that is being replaced. The vehicle component model uses fundamental Newton's equations of motion to compute vehicle acceleration from vehicle mass and total force applied to the wheel. The acceleration is integrated to compute vehicle speed, which is then fed backwards to compute the speeds of the power source components (engine and electric motor). All VPSET models are associated with an initialization and scaling routine. The initialization allows for user provided data population, while the scaling allows for adjusting user provided data to required specifications.

Accessory	Energy Storage	Electric Machine	Transmission	After Treatment	Engine	Power Controller
Mechanical	Lead Acid	PM Motor	Manual	3 Way Catalyst	Generic	Conventional
Electrical	NiMH	AC Motor	Automatic	Electrically heated		Series hybrid
	Li-Ion	PM Generator	Auto Manual	Oxidation Catalyst		Parallel hybrid
	Ultra capacitor	AC Generator	CVT			

Table 1. The components of the principal sub-libraries within the Powertrain Components Super library

For hybrid powertrains, two power paths for the motor torque to the wheels are supported. In the upstream configuration, the motor is upstream of the transmission, which results in the additive torque of the motor and engine to be passed to the transmission. In the downstream configuration, the motor is configured to be downstream of the transmission, which results in the motor torque to be added to the wheels in after the transmission. This allows vehicle configurations with wheel motors to be modeled.

2.1 Energy Storage Library

The energy storage library contains two devices, namely: (a) batteries of three chemistries (Lead acid (LA), Nickel Metal Hydride (NiMH), and Lithium Ion (Li-Ion)) and (b) peaking devices, such as ultra capacitors. The battery models are based on an Equivalent Circuit Model (ECM). This approach to simulating battery behavior is consistent with previous techniques used in the literature [2]. The inputs to the battery model is desired discharge (negative) or charge power (positive), the outputs are: (a) estimated state of charge (SOC); (b) estimated available

discharge power; (c) estimated available charge power; (d) estimated energy capacity; (e) estimated battery efficiency.

2.2 Electric Machine Library

The electric machine library contains models of both electric motors (AC induction and PM) and generators (AC synchronous and PM). The models compute the power (electrical in the case of the generator and mechanical for the motor) produced while accounting for inverter and electric machine efficiencies. All the parameters of the electric machine library (torque – speed characteristics for continuous and peak operation) are based on tabular data. The inputs to all electric machine models are: (i) torque command, (ii) charge power limit; (iii) discharge power limit; and (iv) input torque and inertia (for the generator models) or input speed (for the electric motor models). The outputs are: (i) power produced by the electric machine; and (ii) speed (for the generator models) or torque (for the electric motor models).

2.3 Transmission Library

The transmission library contains models of an automatic, a manual, an auto-manual, and a continuously variable transmission (CVT). All models implement shift logic, torque converter clutch lock up logic (for automatic transmissions), and transmission and axle losses. The vehicle speed that is computed from the vehicle dynamic model is used to compute rotational speeds of upstream components. The torque and inertia from upstream components are passed downstream to the vehicle dynamic model, while accounting for appropriate transmission gear and final drive ratios. The transmission shift logic is based on a table look-up using accelerator pedal position and vehicle speed as the inputs. The clutch lock schedule for the torque converter of an automatic transmission is based on vehicle speed alone. The inputs of all transmission models are: (i) driver accelerator position; (ii) upstream torque and inertia; and (iii) vehicle speed. The outputs are: (i) Shift in progress status; (ii) downstream torque and inertia; and (iii) rotational speed of the upstream power sources

2.4 Engine Library

The generic engine model of this library applies to both gasoline and diesel engines. The engine characteristics such as hot and cold torque-speed curves (both max and friction torque), fuel rate as a function of speed and torque, emission rates for HC, CO, NO_x, and PM as a function of speed and torque, engine warm-up and cool-down time constants are tabular data provided by the engine manufacturer. These maps are then used by the model to compute the instantaneous fuel rate and torque produced by the engine. The inputs of the generic engine model are: (i) engine torque command; (ii) engine speed; (iii) engine on/off command; and (iv) mechanical accessory power. The outputs are: (i) net engine torque after satisfying the mechanical accessories; (ii) fuel rate; (iii) emission rates; and (iv) engine rotary inertia.

2.6 Power Controller Library

The power controller library contains generic conventional, series and parallel hybrid powertrain controllers. The driver interacts with these controllers via an accelerator or brake pedal position, which is converted to a torque demand at the wheels. In the case of the conventional powertrain, the accelerator pedal is the engine torque command. In the case of a hybrid powertrain, the power controller determines the optimum split of the driver demanded torque between the engine and electric motor, given the torque constraints of both and the power limitation of the battery, such that an energy balance between all components is satisfied. The power controller will first attempt to satisfy the driver torque demand with the electric motor alone. If this is possible, the engine goes to an idle state, meeting mechanical auxiliaries. If the motor alone can not meet the driver requested torque, the power controller will always attempt to keep the engine operating at best efficiency. For the series and parallel power controllers there are a total of 16 different control strategies that are supported. The controller will always attempt to keep the battery SOC between the user provided max and min values. Regenerative braking is also handled within the power controller. The battery SOC determines the split between service (manual) brake and electric motor regen.

3. VALIDATION

Validation of a M&S tool is mandatory to build confidence in the tool's ability to model the real world and make predictions that are consistent with reality. Validation of a vehicle M&S tool should be done at two main levels: (a) at the component level to ensure that conservation of energy is not violated and efficiency computations are in line with reality; (b) at the vehicle level to ensure that fuel economy and performance predicted by the tool is in line with vehicle test data collected in the field. To satisfy the first validation level, VPSET has a utility that computes the total energy that goes into and out of each component of the vehicle and computes an average efficiency for the entire simulation. The following sections discuss the validation results of VPSET at the vehicle level.

3.1 HMMWV M1097 A2

The HMMWV M1097 A2 is a higher payload capacity cargo/troop carrier configuration of the HMMWV family of military vehicles.

Figure 2 shows a comparison of VPSET predicted and vehicle field data for a full acceleration test. The vehicle speed in Figure 2 is in miles per hour.
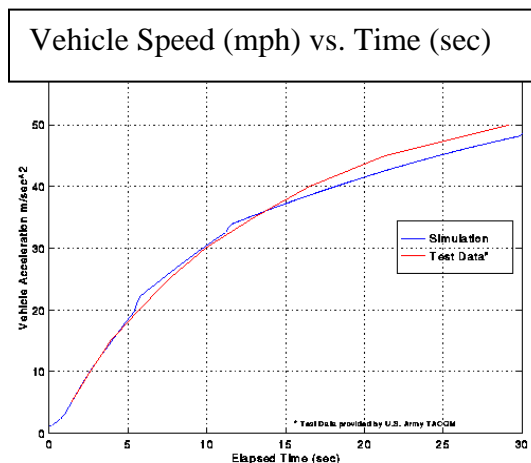
Table 2 summarizes a comparison of fuel economy predictions of VPSET and field data for the HMMWV M1097 A2 over various military driving cycles. As is evident in Table 2, the error in prediction varies from -23% to 16% for the Munson driving cycle and 7% to 13% for the Perryman driving cycle. This is due to the difference in actual vehicle data (engine and transmission details) and data used for the simulation. It is practically impossible to obtain complete vehicle data without the full cooperation of the OEMs of the various components of the vehicle.

Figure 1. Comparison of VPSET Simulation versus field data for a Full Acceleration Test of a HMMWV M1097 A2

Test Driving Cycle	Vehicle Speed (mph)	Measured Fuel Economy (mpg)	VPSET Predicted Fuel Economy (mpg)	Error in Fuel Economy (%)
Munson	14.1	8.7	7.3	16
Munson	22.3	9.8	10.2	-4
Munson	28.5	8.7	10.7	-23
Perryman	31.2	12.7	11.8	7
Perryman	37.6	11.6	10.4	10
Perryman	41.1	11.1	9.7	13

Table 2. Comparison of Fuel Economy predicted by VPSET with Measured field data over multiple driving cycles.

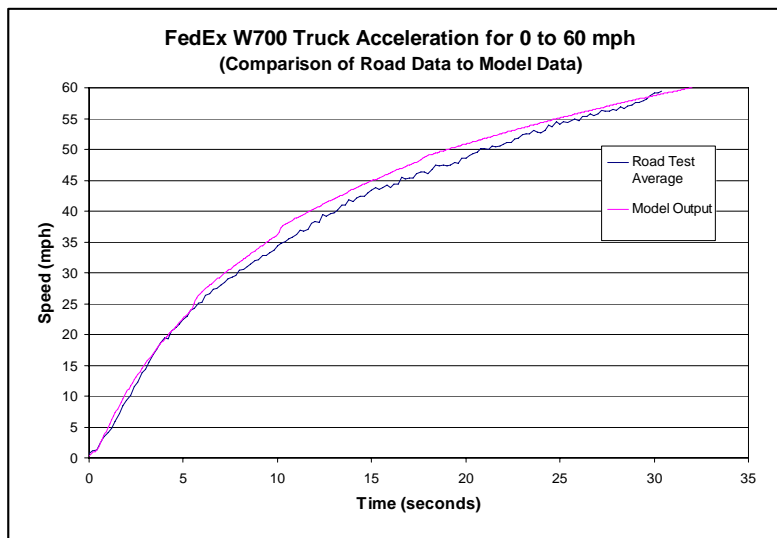## 3.2 CLASS VI COMMERCIAL VEHICLE

Figure 3 shows a comparison of VPSET prediction and vehicle field data for a full acceleration test of a Class VI commercial vehicle with a weight of 15000 lb. Table 3 summarizes a comparison of the performance metrics of the simulation shown in Figure 3. As can be seen from Figure 3, model and test data agree well for vehicle speeds up to 25 mph and beyond 55 mph.

Figure 2. Comparison of VPSET Simulation versus Field Data for a Full Performance Test on a Commercial Class VI Vehicle

Performance Metrics	Measured Value	VPSET Predicted Value	Error in Prediction (%)
0 to 60 mph	32.2 sec	32.1 sec	0.3
40 to 60 mph	18.8 sec	20.3 sec	-8
Max Grade at 55 mph	Not measured	4.9 %	N/A
Max Grade at Launch	Not measured	21.3 %	N/A

Table 3. Comparison of Performance Metrics Predicted by VPSET with Measured field data

4. CONCLUSIONS

This paper presents a general purpose vehicle M&S tool that has the ability to model a conventional or a hybrid powertrain. The tool is based on table look up data provided by the user via a GUI. The tool has been extensively validated at the component level and validation at the vehicle level is presently ongoing. The primary use of the developed tool is for fuel economy prediction and vehicle performance analysis. However, the tool has been used in various hybrid vehicle integration projects for component sizing, deriving component specifications, and control strategy optimization. This tool has been used to analyze a wide range of automotive applications spanning from motor cycles to 100,000 lb military vehicles (HEMTT – Heavy Expanded Mobile Tactical Truck).

5. ACKNOWLEDGEMENTS

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